It the 21 years since its launch, the Voyager I spacecraft has traveled over 6.5 billion miles from Earth. It has made its way out of our solar system and into the heliopause - the boundary between the end of the Sun's magnetic influence and the beginning of interstellar space. Voyager acquired the kinetic energy for its journey through a combination of gravity assist maneuvers using planets it visited during its tour of the solar system, and from its chemical thrusters.

In October of 1998 a new era arrived in propulsion technology with the launch of NASA's Deep Space 1 mission. DS1 carries an ion engine - a device that ionizes and electrostatically accelerates xenon propellant to roughly 10 times the velocity that fuel is ejected from Voyager's engines, albeit at a much lower propellant flow rate. High propellant exhaust velocity, which is proportional to the more commonly used parameter called specific impulse, results in much more efficient use of propellant mass. Ion engines will enable many of the exciting new deep space robotic missions whose propulsion requirements are too difficult, and therefore too expensive, to be performed with traditional chemical thrusters. Such missions include outer planet orbiters, landers, and even sample-return missions.

However, ambitious future missions into deep space will require propulsion systems capable of imparting much greater momentum to spacecraft than chemical thrusters, gravity assists, or even today's ion engines can deliver. These missions could include piloted trips within the solar system or even fast robotic voyages into interstellar space. What propulsion system could revolutionize space transportation so dramatically?

For decades, engineers and scientists have considered the use of **fusion energy** to propel **spacecraft** on journeys faster and further than ever before. Fusion reactions release on the order of $10^{14}$ Joules of energy per kilogram of fuel mass. This **energy density** is over seven orders of magnitude higher than chemical propellants can provide. Furthermore, the fractional conversion of rest mass into energy can be more than seven times greater for fusion than for fission reactions. As such, fusion may enable the high power, thrust, and **specific impulse** needed for human travel to the outer planets and their moons. It could also allow a spacecraft to reach speeds high enough to travel far beyond the edge of our solar system, passing by Voyager early on in its journey.

Fusion provides a source of high energy particles which, for propulsion applications, may be directed to create thrust. Simultaneously, it provides a mechanism for generating a large amount of on-board power where no other power source is available (i.e. far from the Sun). Having an on-board power source allows for spacecraft autonomy and flexibility of trajectory . It permits not just acceleration, but also deceleration of a spacecraft for capture into orbit around a distant planet or moon.

Fusion energy is released when the nuclei of two atoms come close enough to join through the nuclear Strong force, creating a different, heavier element and releasing an amount of energy equivalent to the difference in rest mass of the initial and final products. Initiating fusion requires extraordinarily high temperatures to overcome the Coulomb repulsion between nuclei, as well as long confinement times and high enough particle densities to assure a large number of collisions between particles. It takes a great deal of energy to create the conditions where fusion reactions can occur. Generally speaking, fusion energy output that equals the amount of energy required to create the reaction corresponds to break-even (or a gain of 1).

The world-wide effort to achieve high gain (gain >>1) fusion for terrestrial power plant applications has sought techniques which can provide the necessary confinement and particle densities. Two general classes of confinement techniques have been pursued - inertial confinement and magnetic confinement fusion.

The magnetic confinement fusion approach uses strong magnetic fields to contain a fusion fuel plasma. Currently, the Joint European Torus (JET) is the world's largest magnetic confinement fusion experiment and is located in the UK. JET is a tokamak - a toroidal (doughnut-shaped) magnetic configuration first developed in Russia. Tokamaks are the most developed of magnetic confinement concepts. The International Thermonuclear Experimental Reactor (ITER) is a collaboration between Europe, Japan, Russia, and the United States with plans to build a tokamak two to three times larger than JET. ITER would be the first tokamak facility to produce energy at about the level of an actual fusion power plant.

Inertial confinement fusion relies on laser or particle beams to heat and compress a fusion fuel pellet. The National Ignition Facility at the Lawrence Livermore National Laboratory in California and the Laser MegaJoule facility in Bordeaux, France, are both laser inertial confinement facilities under construction where fusion ignition will be demonstrated in the first decade of the new millennium.

Even if high-gain commercial fusion power becomes a reality here on Earth, there are several challenges unique to developing fusion rockets. Primarily, these challenges pertain to the mass of a fusion powered spacecraft, power produced per unit spacecraft mass (specific power), the availability and storage of fusion fuel, and the direction of energetic reaction products to produce usable thrust.

There have been dozens of fusion rocket concepts proposed. Almost without exception, these concepts project an enormous spacecraft mass of thousands of metric tons, all of which must be delivered to Earth orbit. In comparison, the fully assembled International Space Station will have a mass of approximately 500 metric tons. Such large spacecraft masses correspond to literally hundreds of Space Shuttle launches. Thus, it is apparent that one of the principal challenges for fusion rockets is the cost of launching components from Earth to orbit. Present launch costs are typically between $5,000 and $10,000 per pound, implying that a pound of aluminum launched into orbit is more expensive than a pound of pure gold here on Earth!

A large portion of the rocket mass will necessarily be fusion fuel. There are several possible fusion fuels; the easiest reaction to ignite is that between deuterium (D) and tritium (T) - two heavy isotopes of hydrogen. The D-T reaction yields a neutron and an alpha particle (a helium nucleus). The neutrons are problematic for propulsion applications, as they are not charged, and therefore cannot be manipulated to produce directed thrust; to harness their kinetic energy requires stopping them in a material and making use of the heat generated by their capture. The next easiest reaction to ignite is a D-D burn, which can result in either a neutron and a $^3$He ion, or a proton and a tritium ion. For many propulsion concepts, a more attractive fusion reaction is the one occurring between D and $^3$He. The direct reaction products are protons and alpha particles - no neutrons. Unfortunately, $^3$He is hard to come by on Earth; it is produced in small quantities from tritium decay in nuclear facilities, and in smaller quantities from natural sources. So in addition to the problem of launching a large mass of fuel, there is a significant challenge in finding enough of it in the first place.

Another major challenge is finding a way to direct the motion of the energetic reaction particles so as to result in useful thrust for the spacecraft. Also, it turns out that for a fixed amount of power, it is not always desirable to eject propellant as fast as possible (corresponding to exhaust velocity on the order of $10^7$ m/s for pure fusion reaction products), but rather to "tune" specific impulse and thrust such that the combination is optimized for a particular mission. For example, human exploration of the solar system would benefit from engines that operate at an exhaust velocity in the range of 200,000 - 500,000 m/s. To lower the exhaust velocity of a fusion system necessitates that the fusion plasma be used to heat a much larger mass of hydrogen.

These may seem like daunting challenges to achieving the conditions necessary for exploitable fusion for space propulsion. Nevertheless, there are compelling reasons why we might find solutions.

In the first place, there is every reason to believe that current fusion research efforts are well on their way toward developing systems capable of generating fusion power. A steady increase in the energy produced in experimental fusion reactors has taken place over the last 25 years. Although it is not well known, Halite/Centurion experiments conducted at the U.S. Nevada Test Site using energy from underground explosions to implode an inertial fusion capsule have already allowed the demonstration of excellent performance, putting to rest the fundamental questions about the basic feasibility of achievinghighgain.

Secondly, in 1996, the Fusion Energy Sciences Advisory Committee of the U.S. Department of Energy met to discuss policy regarding major U.S. fusion facilities and alternative confinement concepts, where "alternative" refers to confinement configurations other than the tokamak. Some examples of alternative concepts for magnetic confinement fusion at the basic research phase include Reverse-Field Pinches (RFP), the Field Reversed Configuration (FRC), and the Spherical Tokamak. The committee made a positive recommendation for investment in science and innovation in alternative concepts - an area that had been lacking support since 1991. Some of the alternative fusion confinement concepts may lead to systems more amenable to propulsion applications by enabling smaller scale (and therefore lower mass) devices. The features that make a fusion reactor more attractive for propulsion may also lead to the ultimate success of terrestrial fusion power sources. Smaller unit size, eased magnet requirements, less stringent materials requirements, and reduced recirculating power are all such desirable attributes.

One long term solution to the problem of large propellant mass is simply to make use of fusion fuel from extraterrestrial resources - a technique referred to as In-Situ Resource Utilization. The lunar poles, Mars, moons of outer planets, and comets may all be sources of hydrogen (derived from water electrolysis) to add to the fusion exhaust for optimized thrust and specific impulse. The Moon and Jupiter's atmosphere may be sources of $^{3}$He needed for the fusion reaction itself. Also, there are other advanced fusion fuels more readily available on Earth, but are more difficult to ignite than D-T, D-D, or D-$^{3}$He reactions. One example is proton-$^{11}$Boron, whose direct fusion products would yield only alpha particles.

The challenge of directing particle trajectories so as to obtain usable thrust is most commonly approached by invoking the use of a magnetic nozzle - a strong magnetic field configured to direct the charged propellant particle trajectories. At present, NASA Lewis Research Center is leading an effort at the Ohio State University and Los Alamos National Laboratory to evaluate magnetic nozzles for advanced propulsion. They are designing laboratory experiments that emulate the high temperatures of a fusion reactor-heated flow by using a gigawatt-level plasma source.

For all of the promise of fusion propulsion, there is one known source of on-board fuel that has an energy density exceeding that of fusion -- antimatter. Antimatter research, while still in its infancy, is tantalizing; at nearly $10^{17}$J/kg, matter-antimatter annihilation reactions release two orders of magnitude more energy than fusion reactions. Unfortunately, current antiproton production worldwide at facilities such a Fermilab in Illinois, Brookhaven National Laboratory in New York, and CERN in Geneva, Switzerland totals only a few tens of nanograms per year.

Nevertheless, progress is being made by taking the first steps in understanding how to trap, manipulate, and store antiprotons. Furthermore, there may be a way of taking advantage of the small number of antiprotons likely to be available in the near future for space propulsion - on fusion systems.

Several approaches to fusion have been suggested which use antiprotons to provide a low-mass trigger for inertial confinement fusion. The fusion fuel would be heated with energetic fission-fragments produced when antiprotons annihilate within the nuclei of heavy, fissionable seed material. The cost and energy required to produce antiprotons is so high that it probably will not be economical to use them in terrestrial fusion power plants. However, their use on a spacecraft may provide a unique solution for maximizing the amount of energy available per unit of spacecraft mass. Antiproton triggered fusion concepts are being investigated under NASA sponsorship. One research activity is the design and construction of a portable antiproton trap at Pennsylvania State University. Also, experiments that will deliver an antiproton beam to a compressed fuel target are underway at Kirtland Air Force Base in New Mexico. It is planned that these tests will demonstrate antiproton-induced fission in a subcritical target. The antiprotons will be delivered to the New Mexico facility in the Penn State portable antiproton trap.

Fusion and antimatter propulsion systems will not be small or inexpensive to develop. However, they will allow the kind of space transportation we can only dream of now. Ultimately, we know that such large projects can be done because such large projects have already been done. As was demonstrated by the Apollo Program, a focused, concerted effort can result in enormous accomplishments on the frontier of Space Exploration. It can be done again.